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Teaching relevant climate change topics in undergraduate chemistry courses: Motivations, student misconceptions, and resources

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This short review gives an overview of recent publications on public views on climate change, student views and misconceptions, and resources for making connections in the classroom and the laboratory between chemistry concepts and climate change concepts.

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Scientific consensus and public perception

The scientific consensus is that the climate system is warming and that human activity is extremely likely to have been the dominant cause of the warming since the mid 20th century [1]. Scientific societies have produced both summary documents for the general public that present the evidence that global climate change is occurring, discuss its impacts and anticipated impacts, and present potential courses of action to reduce those impacts [2–5]; as well as reports for educators [6,7]. Despite the high degree of scientific consensus on anthropogenic climate change and efforts to communicate this to the public, studies show that the public's views on climate change vary [8–10]. Lee's analysis of data collected in a Gallup poll of people in 119 countries demonstrates that education is the strongest predictor of climate change awareness, but perception of the risk posed by climate change is predicted by many factors including belief that climate change is anthropogenic, perceptions of local temperature change, dissatisfaction with local air quality, and views on government environmental preservation efforts [8]. In a meta-analysis of studies of climate change beliefs from 56 countries, Hornsey reports that the demographic variable that has the strongest correlation with belief in climate change is political affiliation, while scientific knowledge, trust in scientists, concern for the environment, and belief that there is a scientific consensus about climate change all correlated with a belief in climate change [9]. Kahan reports somewhat different correlations from a survey of adults in the U.S, finding that knowledge of science, as measured by an eight-question survey [10], did not correlate with perception of risk posed by climate change. To the contrary, respondents who scored higher on the survey expressed slightly less concern about the risks posed by climate change [10]. Frequently updated additional polling and analysis of the U.S. public's views on climate change and perception of risk and correlations with demographic variables and political beliefs can be found at the Yale Program on Climate Change Communication website [11].

Student views on and understanding of climate change

Perhaps not surprisingly given the diversity of views on climate change among adults in the U.S., the messages being communicated to students in U.S. middle and high schools (grades 7–12) are inconsistent. A recent study of 1500 science teachers found while that 74% report devoting one or more class period to recent global warming, 31% of those teachers report that they teach seemingly contradictory positions that (1) the scientific consensus is that recent global warming is caused by human activity and (2) many scientists believe that recent global warming is natural [12]. Further muddying the waters for U.S. teachers is a recent well-resourced disinformation campaign, which is seeking to send the booklet "Why Scientists Disagree About Global Warming" to every public school teacher in the country [13]. If many students in U.S. public middle and high schools are getting conflicting information, what are the views of post-secondary students and what opportunities are they getting to learn about climate change?

First year engineering students (N = 637) at ten colleges and universities in the U.S. were asked to what extent they agreed or disagreed with the statement that climate change is caused by humans. The 2017 study found that 47% of the students either strongly agreed or agreed with this statement, while the remaining 53% were either neutral or disagreed [14]. A 2017 study of prevalence of climate change courses at ninety highly ranked colleges and universities in the U.S. estimates

that at these institutions, there is a 0.17 probability that a student will take a climate change course as part of their general education [15]. This study analyzed the disciplinary area of the courses and found that the area with the highest percentage of courses addressing climate change was the natural sciences, followed by mathematics and then social science.

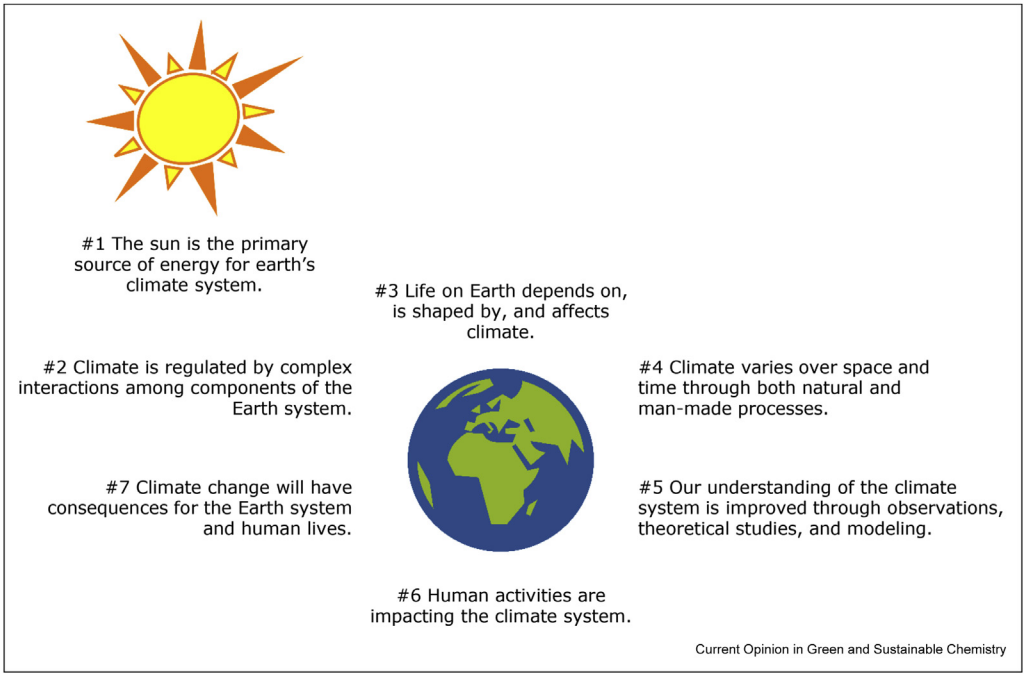
Climate change is an inherently interdisciplinary topic. Understanding Earth's climate system and human perturbation of it draws upon all areas of the natural sciences. Discussions of the impacts of climate change, the actions needed to reduce the risk of further climate change, and the actions needed to adapt to climate change draw upon many areas of the social sciences and humanities in addition to the natural sciences. Interdisciplinary courses on climate change have been developed at post-secondary [16,17] and secondary institutions [18], and have the potential to develop both students' understanding of climate change and of the connections between disciplines. Though interdisciplinary courses may be the ideal environment for students to learn about climate change, at this time there are far more students enrolled in general chemistry or introductory biology courses. Connecting the concepts in these introductory science courses to climate science and climate change concepts is a way to reach a much higher proportion of undergraduate students [19]. Teaching chemistry concepts in the context of societal issues is a well-established and researched pedagogy at both the secondary and post-secondary levels [20–25]. The primary focus in a chemistry course will of course be chemistry concepts, but connections made to the central ideas outlined in the U.S. Global Change Research Program's *Climate Literacy: The Essential Principles of Climate Science* [26] (Figure 1) can facilitate students' reflection on how climate science concepts learned in the context of chemistry connect to the broader understanding of climate change.

Over the past twenty years, there have been many studies on students' understanding of and misconceptions about Earth's climate system and climate change [27–36]. Though many of the misconception studies were done with middle or high school students, Versprille et al. [35,36] and Huxster et al. [34] found that undergraduate students share the many of the same misconceptions. Some misconceptions such as thinking that distance from the sun (rather than axial tilt) is the cause of seasons or confusing climate and weather have little to do with chemistry, but many areas of confusion for students are strongly connected to chemistry concepts (Table 1).

Resources for teaching relevant climate change topics in chemistry courses

CLEAN (Climate Literacy and Energy Awareness Network) has a peer-reviewed collection of over 700

Figure 1


#1 The sun is the primary source of energy for earth's climate system.
#3 Life on Earth depends on, is shaped by, and affects climate.
#2 Climate is regulated by complex interactions among components of the Earth system.
#4 Climate varies over space and time through both natural and man-made processes.
#7 Climate change will have consequences for the Earth system and human lives.
#5 Our understanding of the climate system is improved through observations, theoretical studies, and modeling.
#6 Human activities are impacting the climate system.
Current Opinion in Green and Sustainable Chemistry

Essential Principles of Climate Science as outlined by the U.S. Global Change Research Program [26].

Table 1

Some student climate change misconceptions and connections to chemistry concepts.

Misconception/Area of confusion	Relevant chemistry concepts	References[a]
"Pollution" is the cause of global warming	Pollutants as specific chemical species that have unique properties and reactivity	[29–32,34,36]
The hole in the ozone layer is the cause of global warming	Atmospheric chemistry and the effects of atmosphere on Earth's heat balance	[27–32,34–36]
No distinction made between the greenhouse effect and the enhanced greenhouse effect	Atmospheric chemistry and the effects of atmosphere on Earth's heat balance	[27,29,30,32,35,36]
Difficulty identifying greenhouse gases, including CO_2, water vapor, and others	Molecular vibrations and IR active molecules, blackbody radiation	[29,30,32,35,36]
No distinction made between different types of electromagnetic radiation (UV, visible, IR)	Electromagnetic spectrum	[28,29,32,36]
Lack of understanding of mechanism by which gases act as greenhouse gases	Particulate nature of gases, absorption and emission of IR radiation by molecules	[29,32,35,36]
Not connecting an understanding of the carbon cycle and human perturbation of it to climate change	Biogeochemical cycles, stoichiometry	[28,30,35]
Lack of understanding of the effect of increased atmospheric CO_2 on oceans	Gas solubility, buffer systems, equilibria, solubility product constants	[33]

[a] Some original references are also cited in these sources.

videos, visualizations, and activities [37,38], though use of the search terms "chemistry" and "undergraduate" narrows the offerings to 40. The ACS Climate Science Toolkit was developed as a resource for professional chemists to further develop their own understanding of climate science [39]. As stated on its website, the rationale for its development was belief that because the understanding of climate science and climate change involves understanding some fundamental chemistry and physics, scientists have a responsibility to discuss climate science concepts with non-scientists in their everyday lives. Though these resources are not specifically intended for undergraduate chemistry students, they can be a valuable resource for students as well as instructors.

Mahaffy and team of chemistry educators and chemistry education researchers developed a set of resources for using climate science as a context for teaching general chemistry [40–42]. They have published a set of concept maps that link core general chemistry concepts, as determined from analyzing textbooks and course outlines, to essential principles of climate literacy (Figure 1) through chemistry key ideas. For example, the core general chemistry concept of equilibrium is linked to essential principle of climate literacy #7 (climate change will have consequences for the Earth system and human life) through the chemistry key idea of "acidification of the oceans by CO_2 and speciation of carbon in the oceans". Mahaffy and coworkers identified four chemistry topics that they found to be particularly suitable for the development of climate-science rich contexts: isotopes, gases, acid-base chemistry, and thermochemistry. The concept maps are a valuable resource for instructors to develop their own context-rich learning materials. As part of this project, Mahaffy and coworkers have also developed as series of interactive visualizations guiding students through topics such as: effect of increased atmospheric CO_2 on the ocean's carbonate buffer system, analysis of ice core data, and the overlap of IR absorption spectra of gases with the wavelengths of IR radiation emitted by Earth [42]. An additional aspect of this project was the development of an instrument to measure general chemistry students' understanding of climate change and relevant chemistry concepts [36].

The ACS Chemistry in Context textbook, intended for non-science majors' courses, introduces chemistry concepts on a need-to-know basis in the context of environment, health, and everyday life [43]. Many of the contexts focus on environmental chemistry and environmental degradation, including chapters on stratospheric ozone and the greenhouse effect of Earth's atmosphere. Flener-Lovitt reported a non-science majors' chemistry course focused on climate change that included engaging the arguments of climate skeptics [44]. Understanding the nature of science is important for all science students, but particularly for non-science majors learning about climate change, developing an understanding of the basis of scientific credibility is essential [45].

Several authors have published activities suitable for the classroom or student problem sets that connect chemistry concepts and skills to climate change. Plotting temperature and CO_2, CH_4, and N_2O concentration data from ice core data sets develops students' skills with graphing large data sets [46]. Calculating carbon footprints can segue into discussing stoichiometry [47]. Calculating the mass of CO_2 emitted per mile driven for internal combustion vs. electric vehicles [48] and plotting CO_2 emitted per distance traveled vs. fuel consumption per distance travelled

[49] demonstrates the relevance of thermochemical and stoichiometric calculations.

Published lecture or outreach demonstrations include: mimicking the greenhouse effect of atmospheric CO_2 by comparing the temperature of an illuminated open dark-bottomed beaker filled with CO_2 to one filled with air [50]; measuring the masses of plastic bottles filled with air, N_2, O_2, or CO_2 to allow an estimation of the relative abundance of CO_2 in air [51]; forming CO_2 and SO_2 by combustion and observing the rate of hydration and extent of pH changes [52]; detecting with a pyranometer IR radiation and its position relative to prism refracted visible light [53]; and demonstrating the fundamental vibrational modes of CO_2 with dynamic macroscopic models [53].

Published student laboratory spectroscopy experiments include: building simple IR [54] or photoacoustic [55] spectrometers to measure IR absorption of gases; calculating the global warming potential of a gas by measuring the average absorption cross section of the gas and using data on the sensitivity of Earth's radiative forcing to the wavelengths absorbed by the gas and on the atmospheric lifetime of the gas [56]. Published laboratory experiments addressing the impacts of climate change include: measuring water heating and ice melting rates [57]; measuring calcite mass loss as a function of pH [58]. Published experiments on carbon capture technology include building a monoethanolamine column [59] or synthesizing a metal organic framework [60] and measuring CO_2 capture. Though a comprehensive discussion is beyond the scope of this short review, classroom or laboratory content addressing energy storage [61,62] and non-fossil fuel sources of energy [63–65] emphasizes other potential solutions to climate change challenges and the important role for chemistry and chemists.

Conclusion

The consensus among climate scientists is that global warming is happening, is already having impacts, and is extremely likely to be human caused. Surveys of the public, high school teachers, and college students demonstrate that this consensus is not necessarily shared or understood. While climate science and climate change are inherently interdisciplinary, many concepts needed to understand the effect of Earth's atmosphere on its climate and the impacts of increased emissions of greenhouse gases require chemistry. Making connections between chemistry concepts and the principles of climate literacy can make for both more relevant and engaging chemistry courses and more climate literate citizens.

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